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TITLE: Polarization Phenomena in N-Nucleus Scattering

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POLARIZATION PHENOMENA IN N-NUCLEUS SCATTERING

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Introduction

"Polarization observables will play an increasingly important role in future studies of nuclei with medium-energy (ME) protons." This may be stated without much chance of future contradiction. Beyond that, however, it is impossible to foresee. There are many isues in nucleon-nucleus physics that could be dramatically affected. I will present a couple of current examples of polarization experiments. Then I will discuss two future experiements in which qualitatively new informtion will be obtained. The emphasis here will be on physics that cannot be obtained from other hadronic or electromagnetic experiments.

From an experimental perspective, it is apparent that ME protons offer a large advantage over low-energy protons ($E < 100$ MeV) when it comes to proton polarization. The much longer range of the higher energy particles results in scattering efficiencies in the 10^{-1} range at 500 MeV compared to 10^{-4} at 50 MeV. The advantage for ME neutrons is not nearly as striking. However, efficiencies are sufficient to allow ($\vec{p}$, $\vec{n}$) studies to be performed.

One can already observe my prejudice for polarization transfer (PT) experiments. Indeed, experiments in which polarimetry is required will be the main subject of this talk. Measurement of analyzing powers (not requiring polarimetry) is so routine today that I will assume these measurements need no special justification or discussion. Spin correlation experiments cannot presently be performed in any general way on complex nuclei. Future machines such as the IUCF cooler should offer a wide variety of possiblities for spin correlation experiments, so the time is approaching when one should begin to think about the physics that might result.

Polarization Transfer Experiments

In general, there are five parity conserving PT observalbes in spin 1/2 incoming-spin 1/2 outgoing reactions. They are D_{NN}, $D_{LL'}$, $D_{SS'}$, $D_{SL'}$, and $D_{LS'}$ in modern notation.[1] Additionally, one has the independent quantities, the polarization, P_N, and the analyzing power, A_N. The subscripts refer to the spin projections indicated in Fig. 1, with L, S, N = longitudinal, sideways, and normal. The relations between the new definitions and older systems used by Wolfenstein[2] and Ohlsen[3] are given in Table I.

TABLE I

New[1]	Wolfenstein[2]	Ohlsen[3]
D_{NN}	D	K_y^y
$D_{SS'}$	R	$K_x^{x'}$
$D_{LL'}$	A'	$K_z^{z'}$
$D_{LS'}$	A	$K_z^{x'}$
$D_{SL'}$	R'	$K_x^{z'}$

In order to measure for example $D_{LS'}$, one needs a longitudinally polarized beam and a measurement of the S' outgoing component. Then $D_{LS'}$ = $P_S^{final}/P_L^{initial}$. The expression for D_{NN} is more complicated and requires A_N and P_N as well.[2,3] Finally, it is often convenient to think in terms of spin-flip probabilities. These are related to the Ds via

$$S_{ij} = \frac{1}{2}\,(1 - D_{ij}) \quad .$$

The Ss vary from 0 to 1, as the Ds vary from +1 to -1.

Elastic Scattering

Elastic scattering from a 0^+ target is particularly simple to analyze. Parity and time-reversal arguments limit the scattering amplitude to a form

$$M(q) = A + C\,\sigma_N \quad ,$$

(where N is the normal component defined previously). Ignoring an overall phase, three measurements suffice to determine M(q).

Two of these are the differential cross section, σ_o and A_N (or equivalently P_N); the third, commonly called the Q parameter[4] requires polarization transfer. In terms of the previously defined quantities,

$$\sigma_o = A^2 + C^2 \quad ,$$

$$\sigma_o A_N = 2\ \mathrm{Re}\ AC^* \quad ,$$

$$\sigma_o Q = 2\ \mathrm{Im}\ AC^* \quad ,$$

with the symmetries,

$$A_N = P_N \quad ,$$

$$Q = D_{LS} = D_{LS'} \cos\theta_{lab} + D_{SS'} \sin\theta_{lab} \quad ,$$

$$= -D_{SL} = D_{LL'} \sin\theta_{lab} - D_{SL'} \cos\theta_{lab} \quad .$$

The first measurement of the Q parameter for a complex nucleus was performed with the focal-plane polarimeter[5] of the high-resolution spectrometer at LAMPF. Figure 2 shows the Q data for the reaction $^{40}Ca(p,p)^{40}Ca$ at $E_p = 500$ MeV. These data, along with A_N data at the same energy, show definite evidence for the inadequacy of impulse approximation calculations based on the

Schroedinger equation (dashed curve, Fig. 2). This has led to the suggestion[6] that the nuclear medium modifies the free N-N interaction even at this relatively high energy. A much better fit to the data could be obtained by Ray et al.[6] if the free N-N spin orbit term were reduced by ~20% at small q.

An alternative propcsal, which has received considerable attention recently, is that relativity plays a role beyond the kinematic constraint built into the intrinsically nonrelativistic Schroedinger-equation-based approaches. In particular, Sherpard, McNeil, and Wallace[7] have achieved a phenomenal success with an impulse approximation approach based on the Dirac equation. The results of the two approaches for the Q parameter are shown in Fig. 2. It is entirely plausible that the need for more careful consideration of relativistic affects is seen in measurements of polarization cbservables. After all, in the Dirac equation spin enters at a fundamental level. More experiments of tnis type are required before one can really assess the succeses of the Dirac equation approaches.

Inelastic Scattering and Charge-Exchange

There is great potential for new physics in polarization transfer studies of inelastic scattering and charge exchange reactions. Here the full complexity of the NN-interaction is allowed. Although detailed studies of these observalbes in the Dirac impulse approximation are only beginning, it seems safe to predict that important differences will arise between this approach and the Schroedinger-equation-based models.

The physics obtainable from polarization observables is most apparent when one uses the eikonal impulse approximation model.[9,10] Expressions for the PT observables closely resemble those for free NN experiments. The major approximations necessary are:

1) Eikonal propagation through the nuclear medium.

2) Static NN interactions only.

3) Reaction Q value << beam energy.

These approximations are fairly accurate for most problems of interest for bombarding energies above 200 MeV.

The main observation we wish to emphasize here is that there are only two form factors measurable for unnatural parity inelastic transitions. Combinations of the PT observables may be formed that isolate, respectively, the transverse, X_T, and axial longitudinal, X_L, form factors. Specifically,

$$X_T^2 F^2 = \frac{1}{4} \sigma_o (1 - D_{NN} + D_{SS'} - D_{LL'}) \quad . \tag{1}$$

$$X_L^2 E^2 = \frac{1}{4} \sigma_o (1 - D_{NN} - D_{SS'} + D_{LL'}) \quad . \tag{2}$$

The coefficients E and F are taken from the impulse approximation NN amplitudes in the notation of KMT.[11] The transverse form factor is identical to that measurable in electron scattering. The axial longitudinal is not present in electromagnetic interactions and thus represents new physics obtainable from polarized nucleon experiments. This form factor is, of course, present in the semileptonic weak interaction.[12] Hence, inelastic scattering and charge-exchange experiments may well provide interesting information in several areas of weak interaction physics. A final note on Eqs. (1) and (2) relevant to the experiments discussed shortly is that they are valid (within the approximations noted) even if unnatural parity excitations are present. Thus, it is not necessary to know, for example, that a (p,p') reaction occurs only through unnatural parity channels.

Recently, considerable attention has been paid to understanding the NN-effective interaction in terms of meson-exchange models.[13,14] A discussion of these approaches is beyond the scope of this talk. Crudely speaking, for the isovector case the axial longitudianl part of the NN interaction results from pion exchange and the transverse part from rho-meson exchange.

I will briefly discuss two planned experiments that attempt to exploit the "new" physics contained in PT experiments to learn something about the axial and transverse nuclear responses.

The first experiment, the $^{13}C(\vec{p},\vec{n}_0)^{13}N$ reaction at $E_p = 160$ MeV is part of an approved proposal at Indiana (Fig. 3). The target was selected because there is accurate data from $^{13}C(e,e')$ yielding the transverse form factor[15] (Fig. 4). If our simple model has its expected range of validity, we should be able to find the same information from the (p,n_0) reaction to the mirror state in ^{13}N. The axial longitudinal form factor will be completely new information. Figure 5 shows calculations of the axial and transverse form factors for this transition using DWBA-70 with the Love-Franey interaction. The nearby curves are the same calculations employing the eikonal model in which Eqs. (1) and (2) are exact. Normalization of the two types of calculations was made at zero degrees. It is apparent that the neglect of distortion and nonstatic interactions is unimportant even at this relatively low energy.

An experiment scheduled to run at LAMPF this fall will employ the HRS polarimeter to make the first (p,p′) measurements of the transverse and axial longitudinal nuclear response functions. This will be accomplished by measuring the entire spectrum of inelastic scattering of 800-MeV protons from 0 to 100 MeV of excitation energy. At each excitation energy the PT observables will be recorded thus allowing one to use Eqs. (1) and (2) to project the corresponding response functions. Figure 6 shows calculations of these response functions in a model that incorporates some of the fascinating spin physics involved when mesons propagate in the nuclear medium.[16] Note that at small q both the axial and transverse functions are suppressed with respect to the free (noninteracting) Fermi gas calculation. At larger q the axial response shows an enhancement, which if it were an order of magnitude larger, might be called a precursor of pion condensation. Clearly this kind of experiment will have a lot to say about the current critical issues of delta-hole effects, short range interaction (g′), and enhancement of meson fields in nuclei.[17]

In conclusion, it is easy to make a strong case for emphasizing polarization observables in future (p,p′) and (p,n) experiments. We have attempted to do this by stressing the new nuclear structure physics obtainable from PT experiments. One may also argue that the effective NN interaction, medium effects, relativistic approaches, etc., are equally interesting frontiers for future study.

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Figure Captions

Fig. 1. Summary of the allowed polarization transfer observables.

Fig. 2. Q parameter data for $^{40}Ca(p,p)^{40}Ca$ at 500 MeV. The curves are calculations from Ref. 7.

Fig. 3. Schematic layout of the proposal $(\vec{p},\vec{n})$ experiment at IUCF.

Fig. 4. Transverse form factor for the ^{13}C ground state from Ref. 15.

Fig. 5. DWIA and eikonal calculations for the transverse and axial longitudinal cross sections for the $^{13}C(p,n_o)^{13}N$ reaction at 160 MeV.

Fig. 6. Calculations of the nuclear response functions from Ref. 16.

Polarization Transfer Experiments
(Wolfenstein param.)

parity conserving observables are:

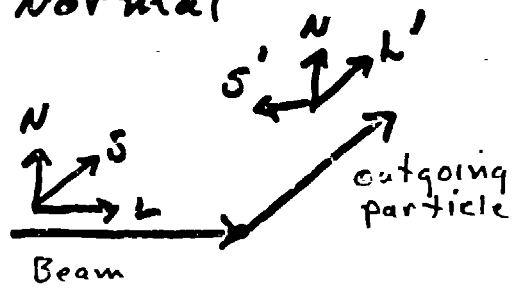
$$D_{LL'},\ D_{SS'},\ D_{NN},\ D_{LS'},\ D_{SL'}\ ;\ P,\ A$$

ex. $P^f_{S'} = P^i_L\, D_{LS'}$

L = longitudinal
S = sideways (in plane)
N = Normal

except

$$\underline{P^f_N} = \frac{P(\theta) + P^i_N D_{NN}}{1 + P^i_N A(\theta)}$$



Spin-flip Prob $\quad S_{ab} = \tfrac{1}{2}(1 - D_{ab})$

$$-1 \le D_{ab} \le 1$$
$$1 \ge S_{ab} \ge 0$$

$$S_{NN} = (\sigma_{+-} + \sigma_{-+}) / \sum_{ij} \sigma_{ij}$$

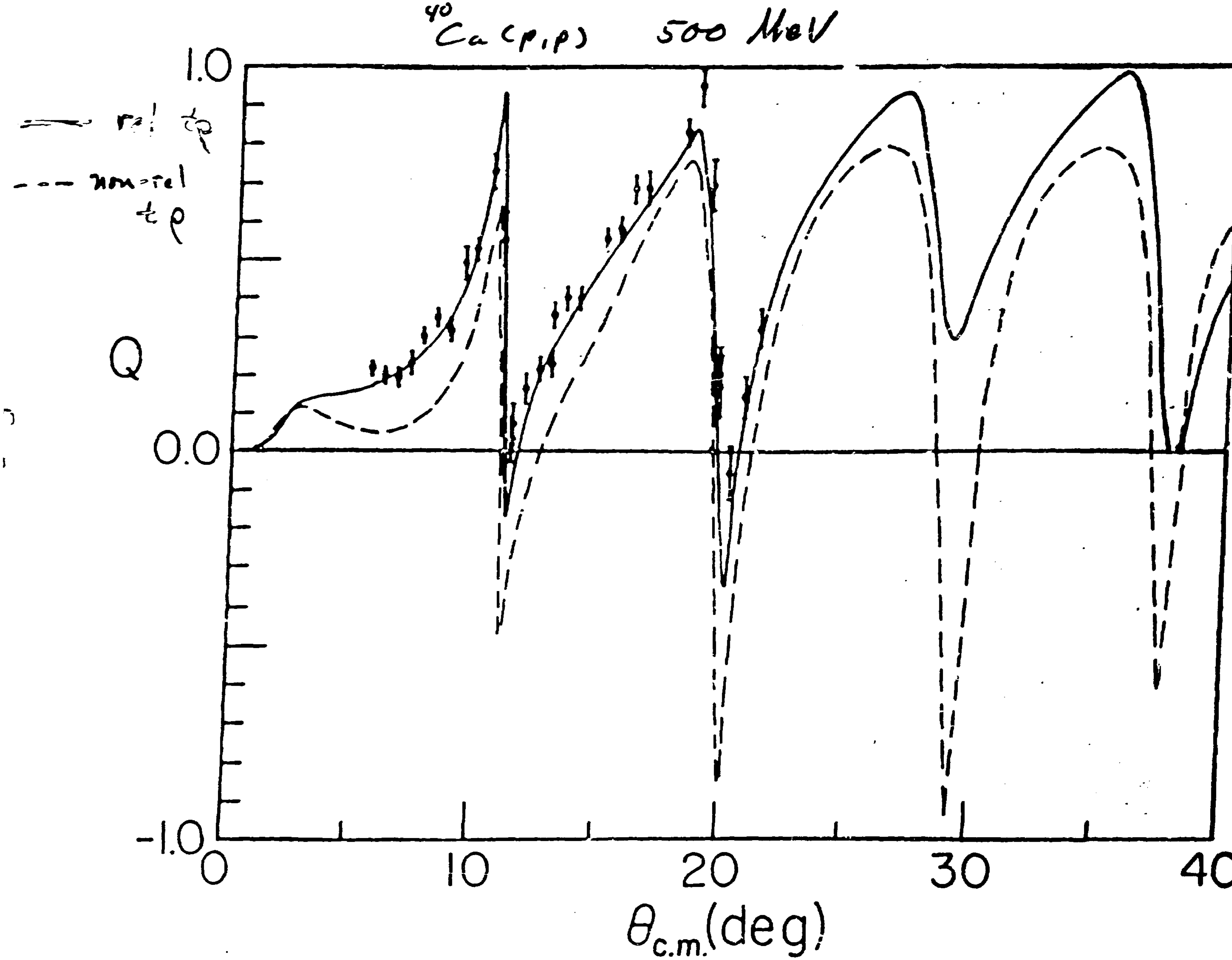
$$P = (\sigma_{++} + \sigma_{-+} - \sigma_{+-} - \sigma_{--}) / \sum_{ij} \sigma_{ij}$$

$$A = (\sigma_{++} + \sigma_{+-} - \sigma_{-+} - \sigma_{--}) / \sum_{ij} \sigma_{ij}$$

$$P - A = 2(\sigma_{-+} - \sigma_{+-}) / \Sigma\, \sigma_{ij}$$

Fig. 1

Shepard, McNeil & Wallace T.K.L.



Polarization Transfer in (p, n)

Los Alamos - IUCF - Ohio Collab.

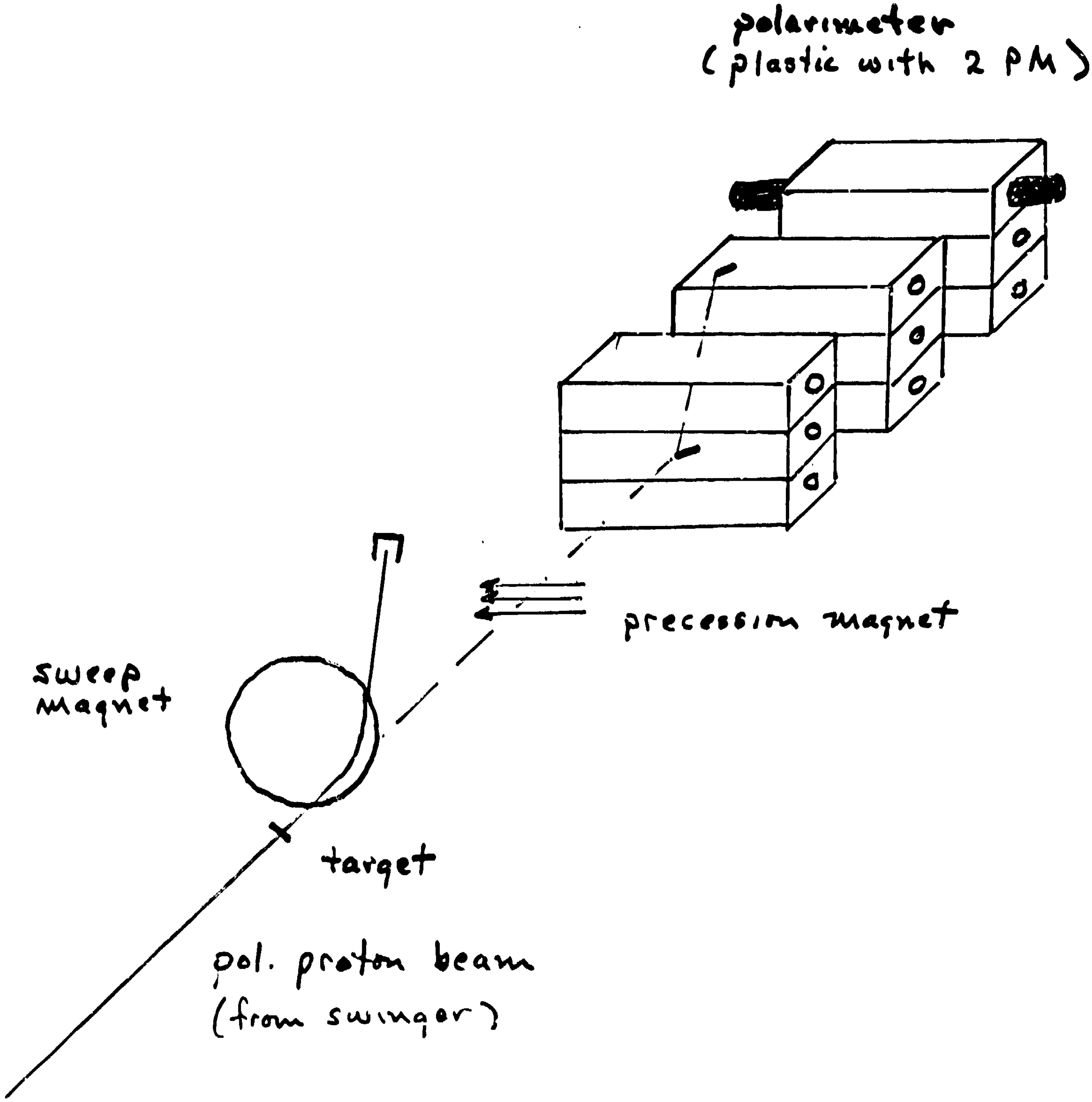


Fig 3

Hicks et al., P.R. C26, 339(1982).

$^{13}C(e,e)$

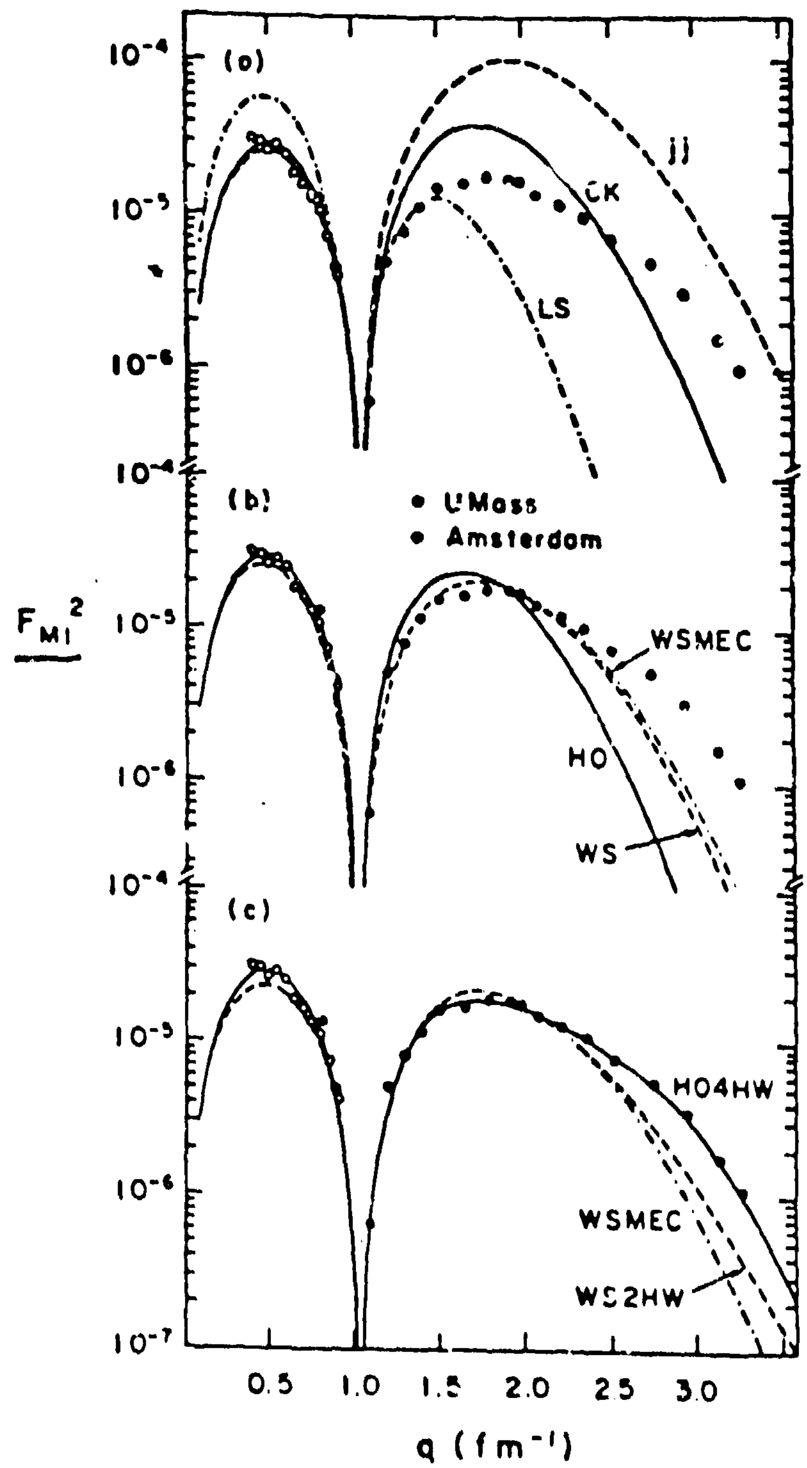
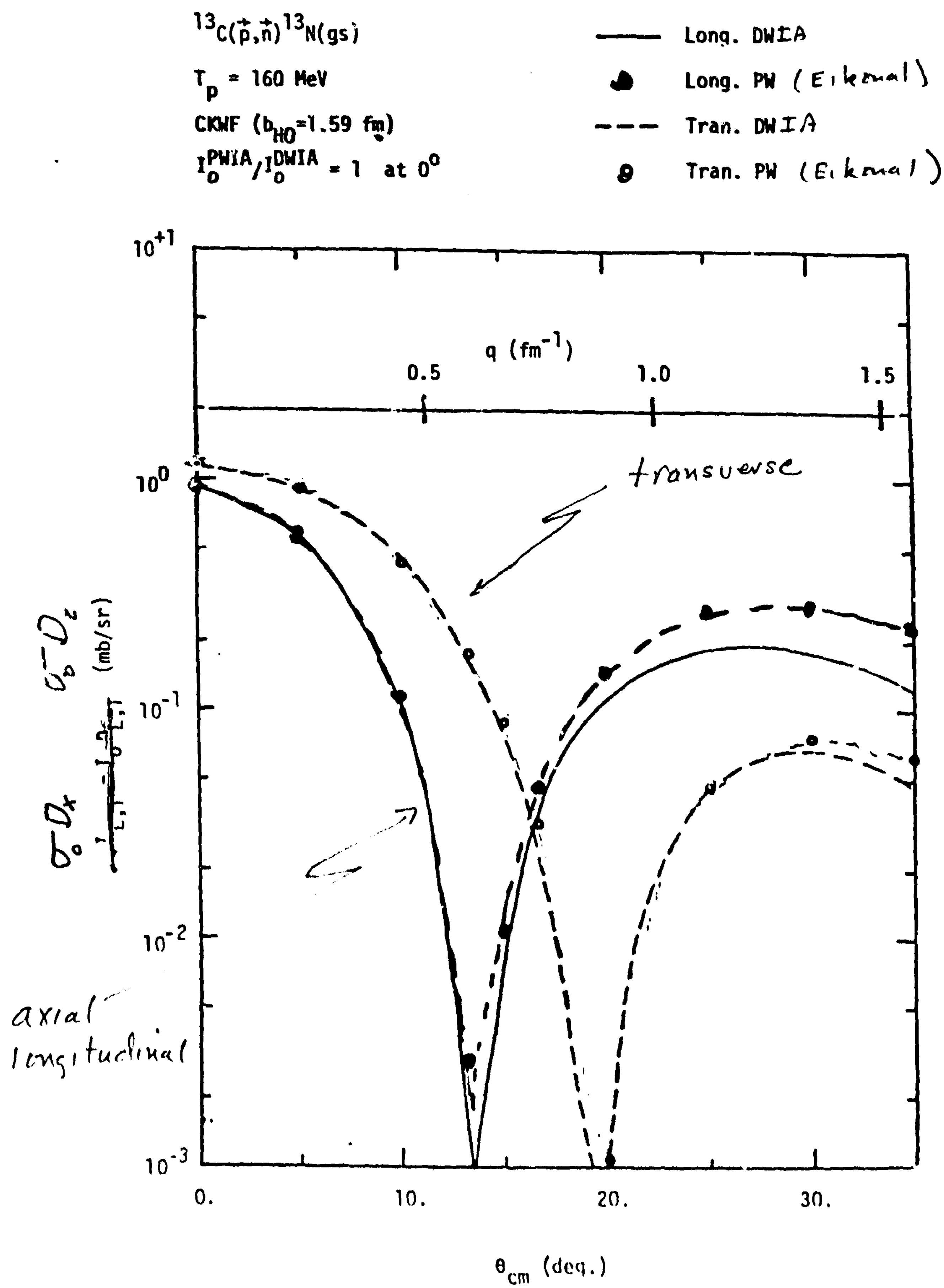


Fig. 4



$^{13}C(\vec{p},\vec{n})^{13}N(gs)$
T_p = 160 MeV
CKWF (b_{HO}=1.59 fm)
I_0^{PWIA}/I_0^{DWIA} = 1 at 0^0
Long. DWIA
Long. PW (Eikonal)
Tran. DWIA
Tran. PW (Eikonal)
q (fm^{-1})
0.5
1.0
1.5
transverse
axial
longitudinal
$\sigma_0 D_z$
$\sigma_0 D_x$
(mb/sr)
10^{+1}
10^0
10^{-1}
10^{-2}
10^{-3}
0.
10.
20.
30.
θ_{cm} (deg.)

Fig. 5

Alberico, Ericson, & Molinari, Nucl. Phys. A379, 429 (1982).

$\vec{\sigma}\cdot\vec{q}$ π Fermi Gas
Longitudinal
$\vec{\sigma}\times\vec{q}$ ρ Transverse

$(g' = 0.7)$

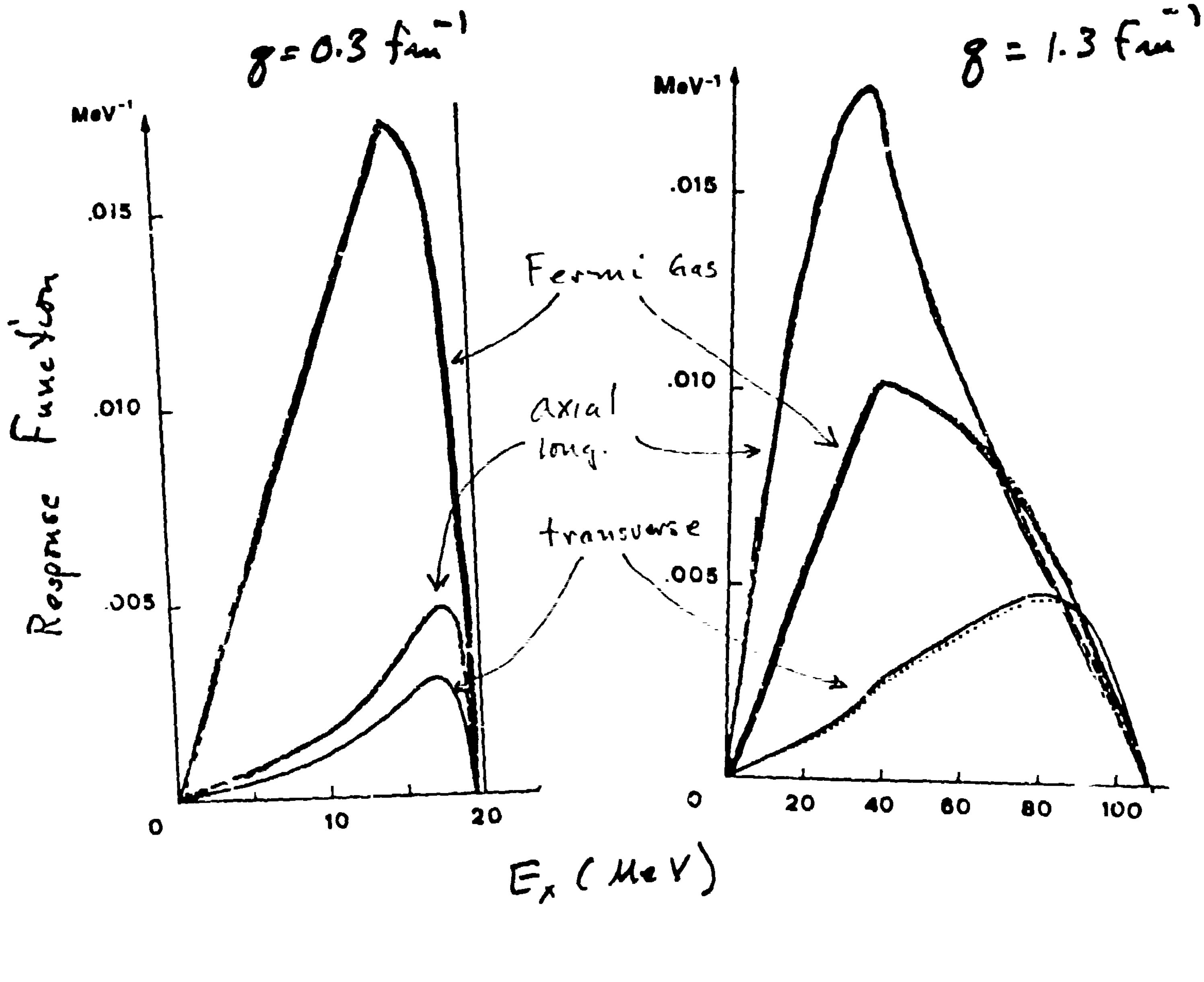


Fig. 6